X-ray Optics at MSFC

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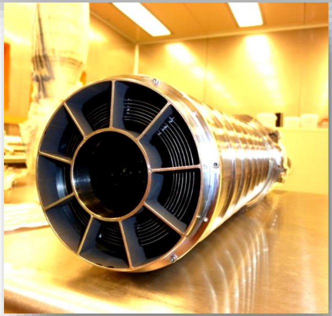
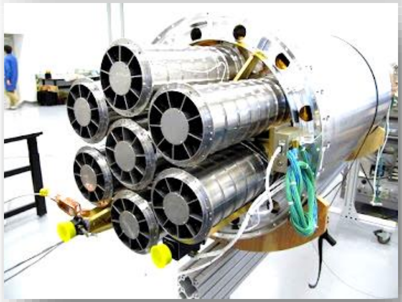
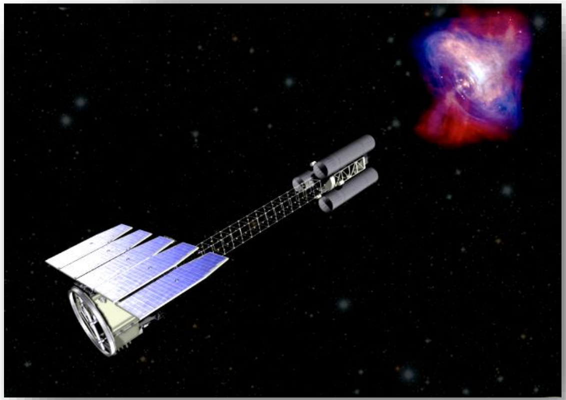
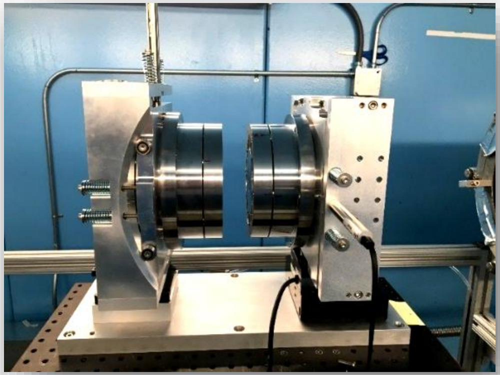
X-ray Optics at MSFC

- MSFC has been developing integrated full-shell X-ray optics for ~ 20 years
- Funded initially through ROSES/APRA program
- Fabrication Approach: Electroformed nickel replication
- Optics have been built for satellite, rocket and balloon-borne missions and for various spin-off applications

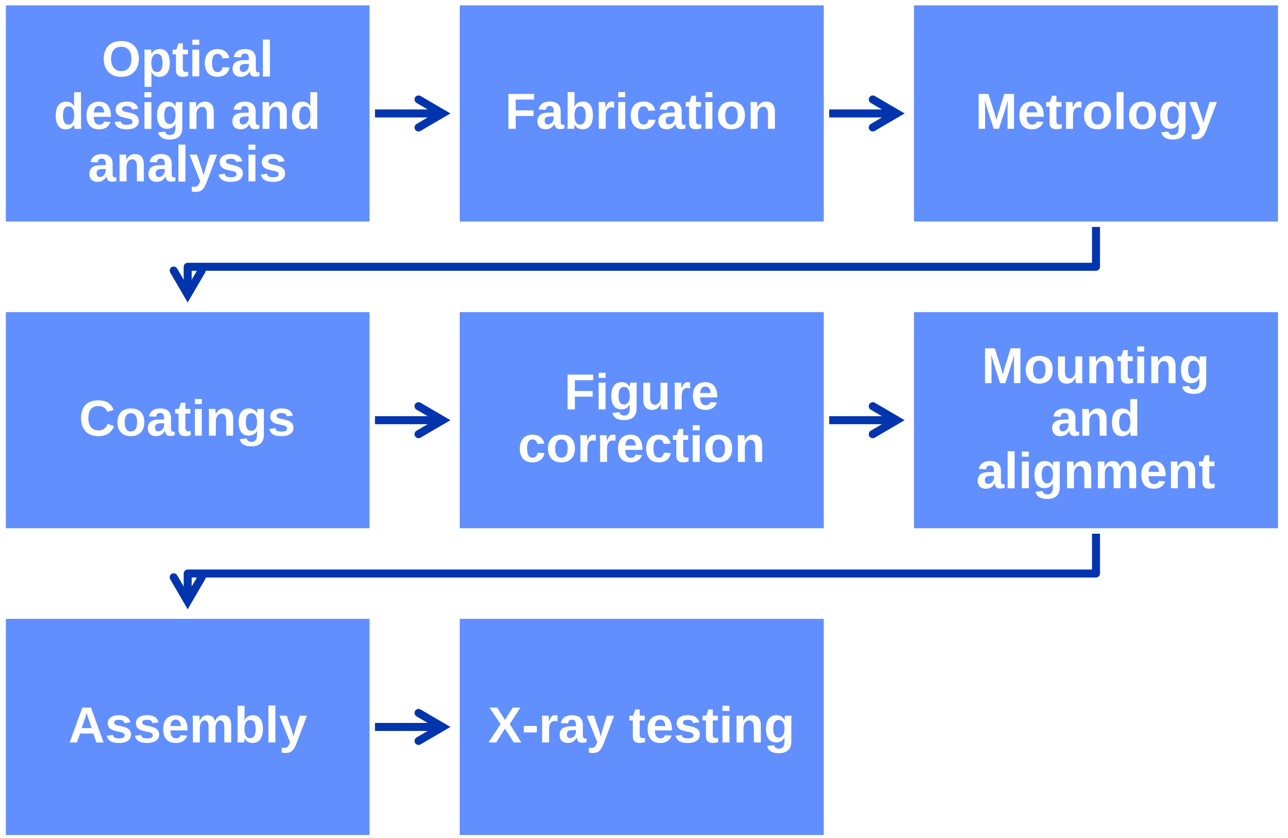






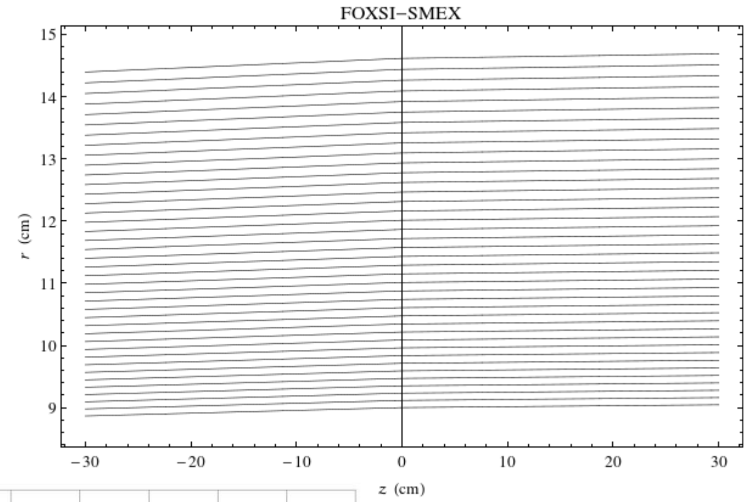


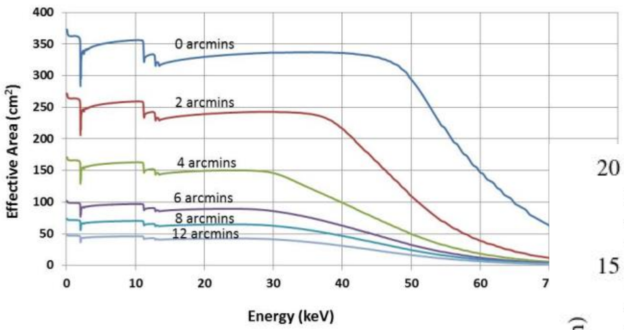
X-ray Optics at MSFC

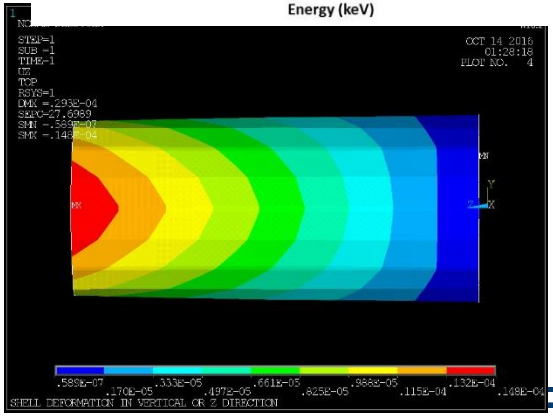


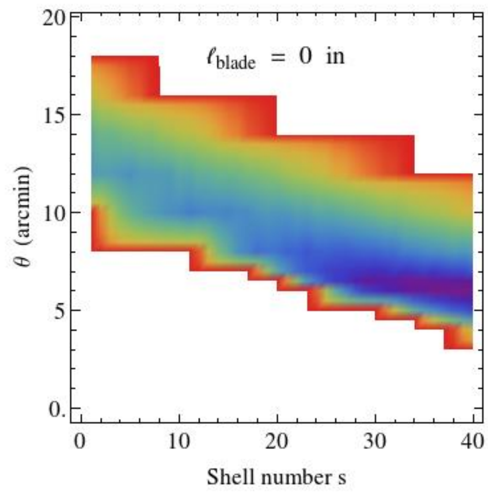
Optical Design and Analysis

- Optical configuration – diameter, focal length, segment length, thickness
- Analytical and Monte-Carlo raytracing to characterize the on-axis and off-axis effective area, angular resolution, FOV
- Stray light analysis
- Coatings – Single and Multi-layers
- FEA
  - Mechanical
  - Thermal





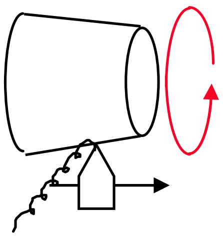




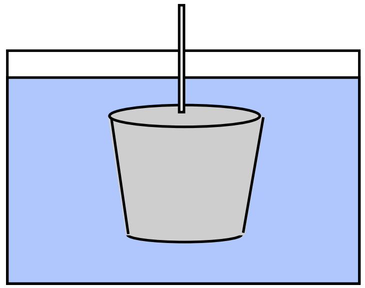
Electroformed Nickel Replication

Mandrel Preparation

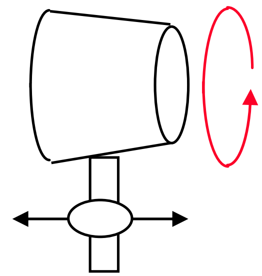
1. CNC machine mandrel from aluminum bar



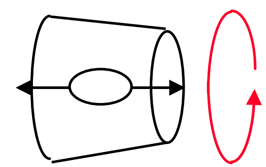
2. Chemical clean and activation & electroless nickel (EN) plate



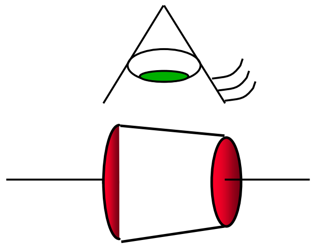
3. Diamond-turn to few 10s nm surface, sub-micron figure accuracy



4.Superpolish to 0.3 – 0.4nm rms finish

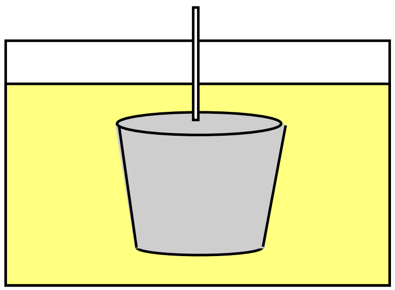


5. Metrology on mandrel

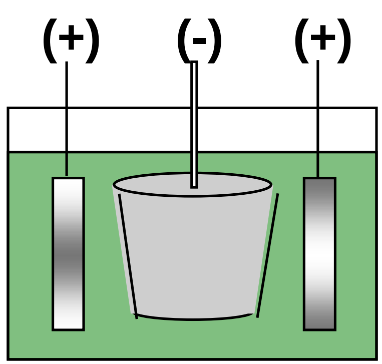


Shell Fabrication

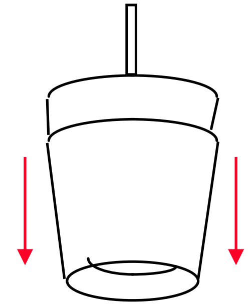
6. Ultrasonic clean and passivation



7. Electroform NiCo shell onto mandrel



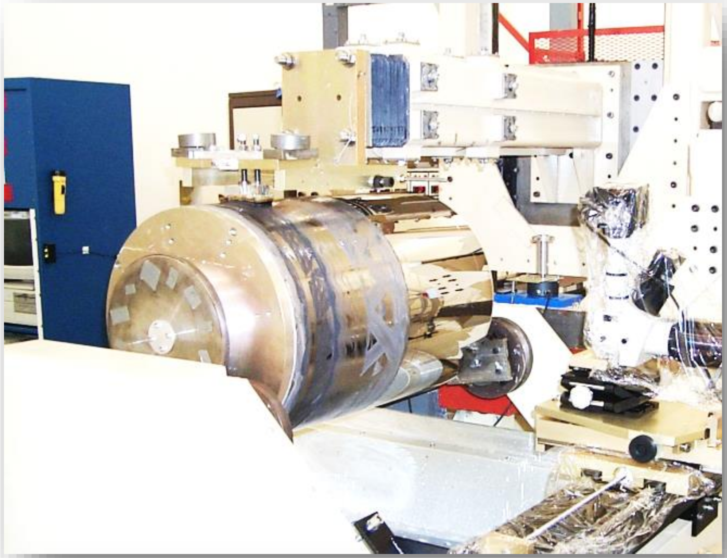
8. Separate optic from mandrel in cold water bath

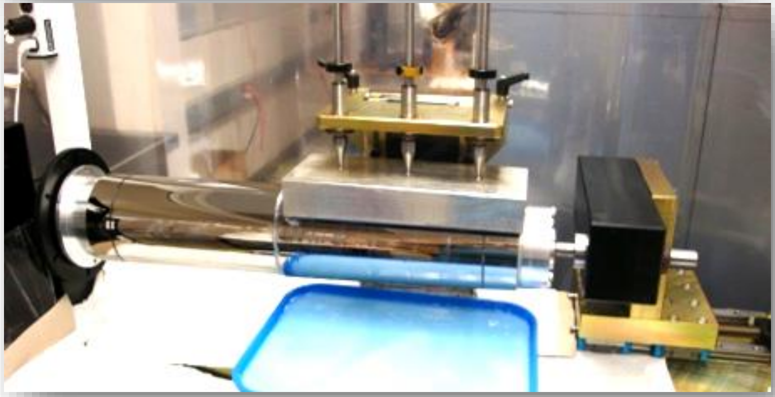


MSFC Infrastructure

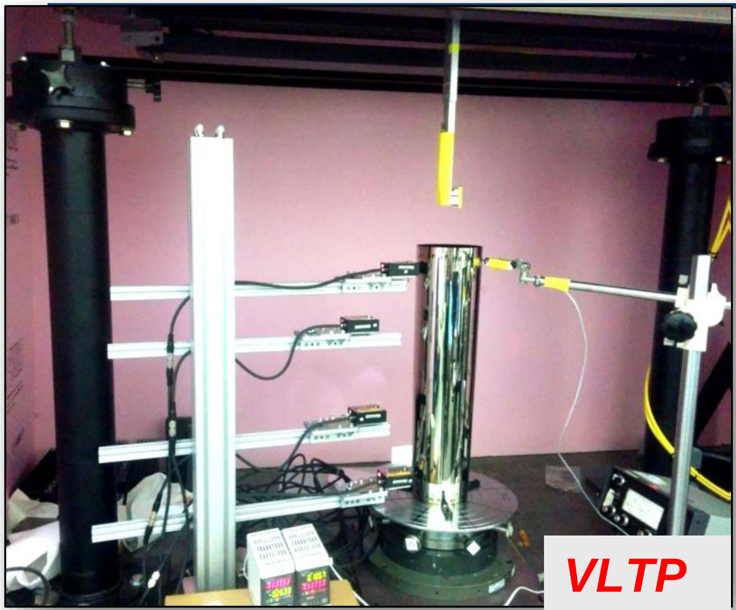
Mandrel Diamond-Turning

Mandrel Polishing



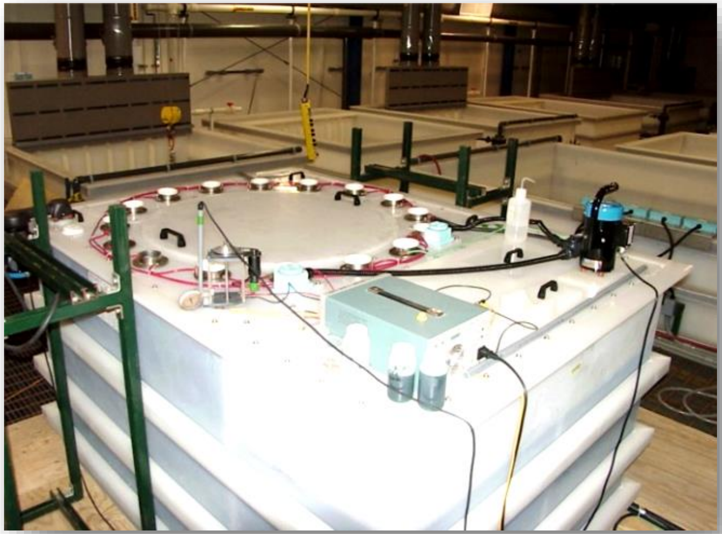


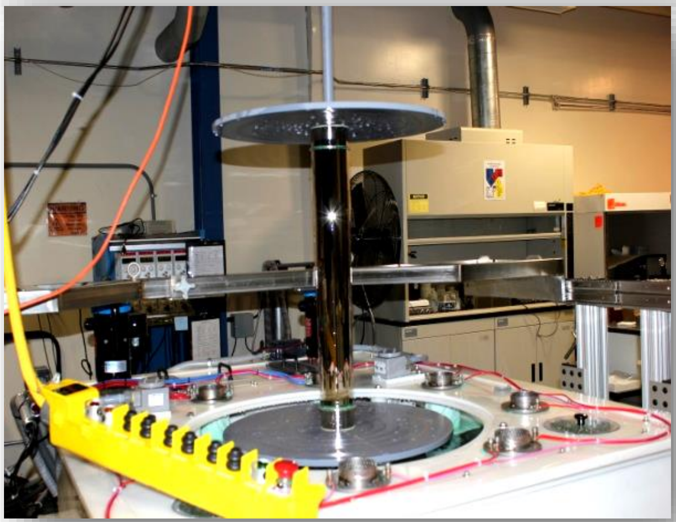
MSFC Infrastructure - Metrology



- Surface profile – Long Trace Profiler (>2mm spatial wavelength), Form Talysurf surface profiler (< 120 mm), Zygo interferometer (mandrel figure metrology)
- Surface roughness - Zygo NewView (spatial sampling range 0.04 to 11.8 microns)
- Circularity - Coordinate Measuring Machine
- Coating characterization - XRR (X-ray reflectometer for density, thickness and roughness),Step Profiler

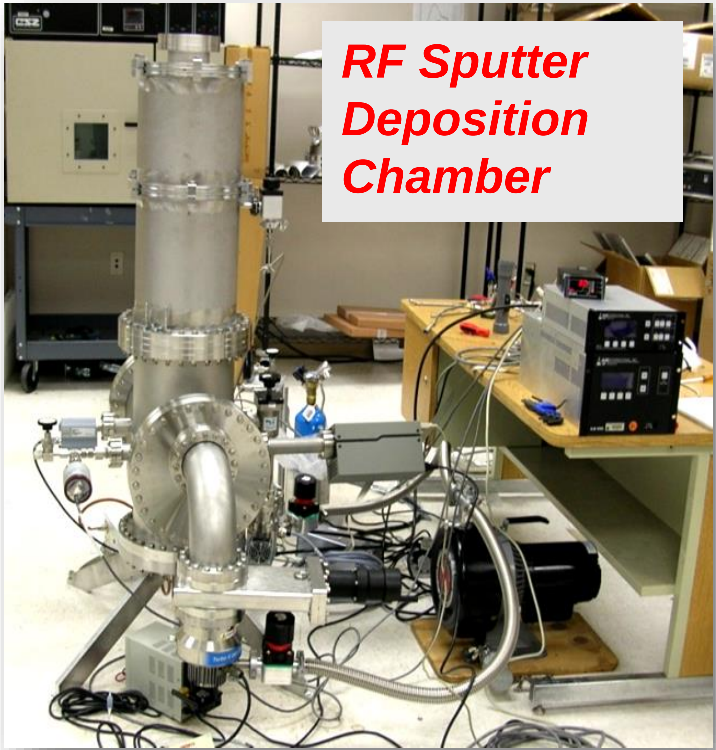
MSFC Infrastructure - Replication





MSFC Infrastructure - Coatings

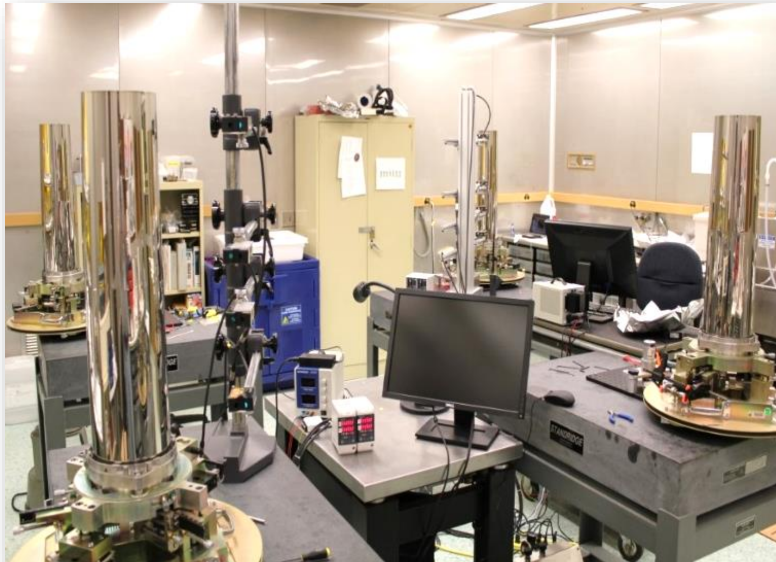
- Custom designed coating chambers for full-shell optics
- RF and DC magnetron sputter deposition
- Underway – Multilayer deposition chamber
- Active research in In-Situ stress measurement and analysis

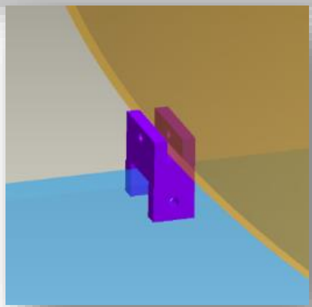


MSFC Infrastructure – Alignment & Assembly

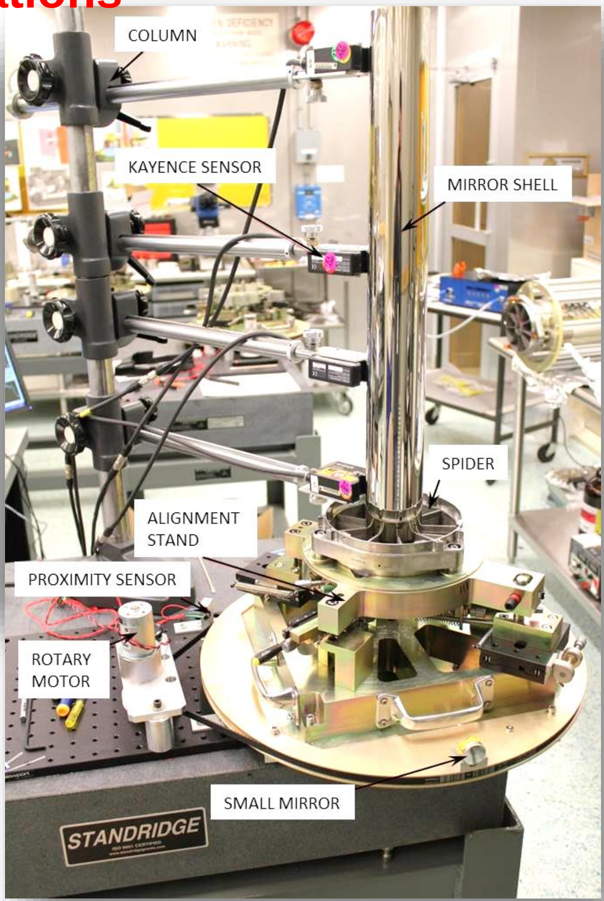
Mirror shell alignment and installation stations

- Shells are glued from one end – less weight for the support system, less obscuration
- General approach: Convert radial displacement into azimuthal one
- The use of the clips minimizes the distortions due to epoxy shrinking



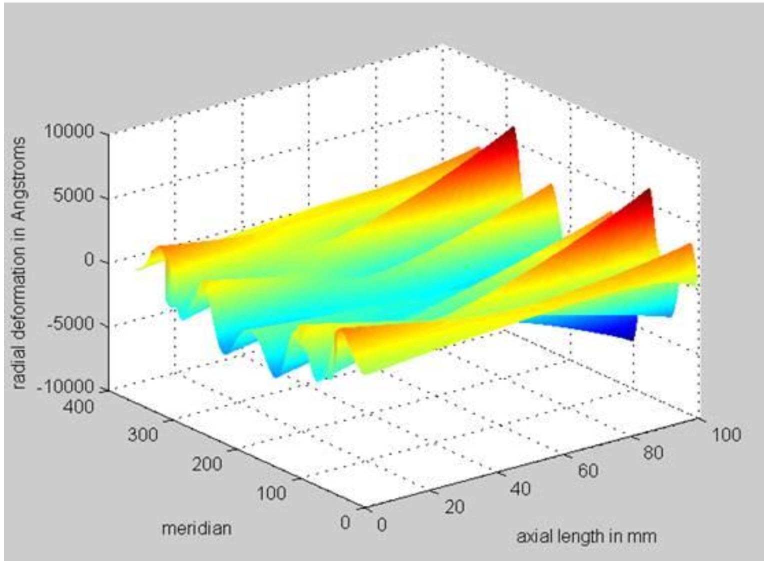


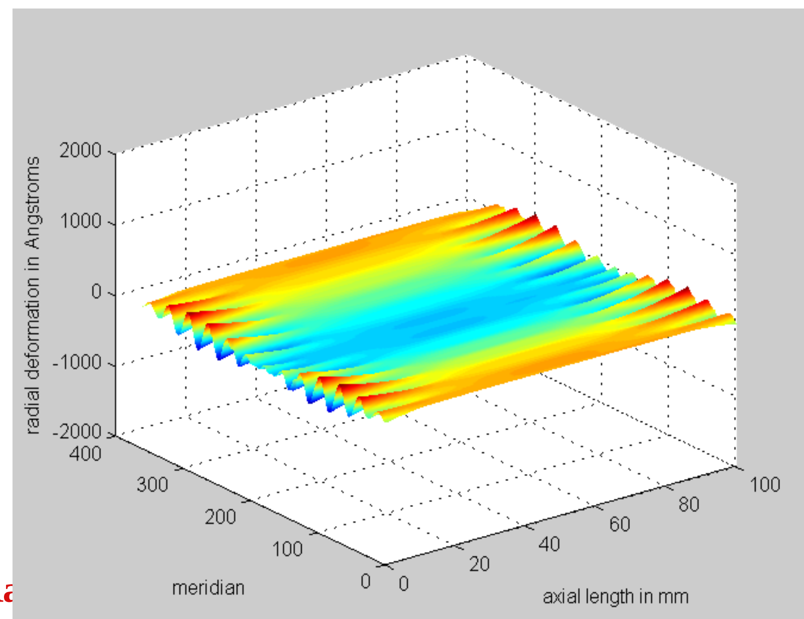
Pre-glued clips minimize the distortions due to epoxy shrinkage



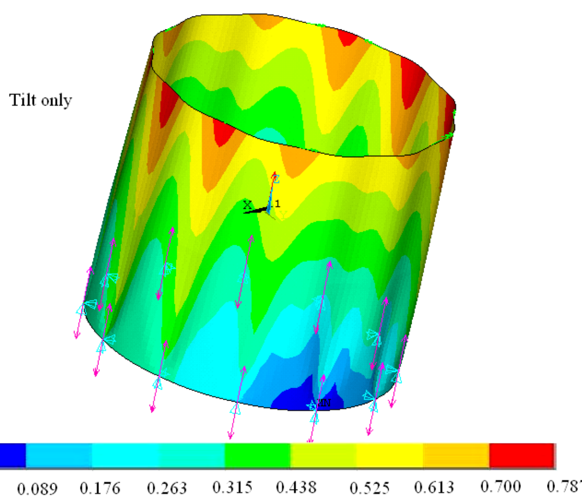
Mikhail Gubarev et.al; Alignment system for full-shell replicated x-ray mirrors. Proc. SPIE 7360, EUV and X-Ray Optics: Synergy between Laboratory and Space, 73600A (April 30, 2009); doi:10.1117/12.823848.

Alignment & Assembly - FEA





- Sensitivity to radial displacements
- Any radial distortion on one edge of the shell leads to distortions on other end of the shell



Deformation maps for the 34 cm diameter, 60 cm length monolithic shell supported with 12 points at the bottom of the mirror. The shell is tilted by 1 microradian. The distortion scale is in microns.

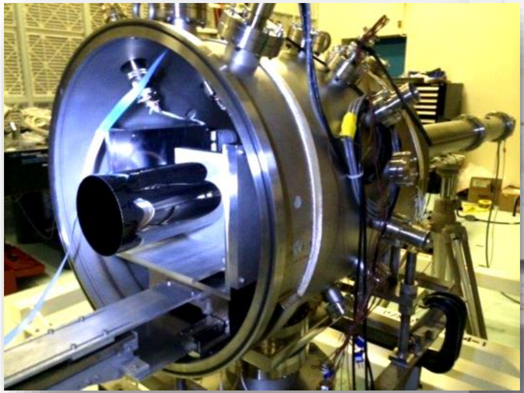
MSFC Infrastructure – X-ray Testing

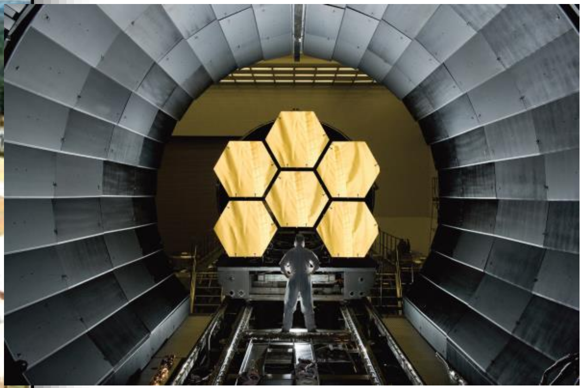
Straylight test facility (SLTF) :

- 100m long vacuum tube
- Clean room facility
- Can accommodate mirrors upto 1m diameter
- Pumped with cryopumps upto 10^{-7} torr

X-ray and Cryogenic facility (XRCF):

- The XRCF is the world's largest optically clean cryogenic and X-ray test facility.
- The facility consists of a 520m-long X-ray guide tube, an instrument chamber, and two clean rooms
- In addition to the large vacuum chamber, the facility has a smaller, more cost-effective cryogenic and cryogenic optical testing chamber for subscale testing of smaller instruments





Optics Applications

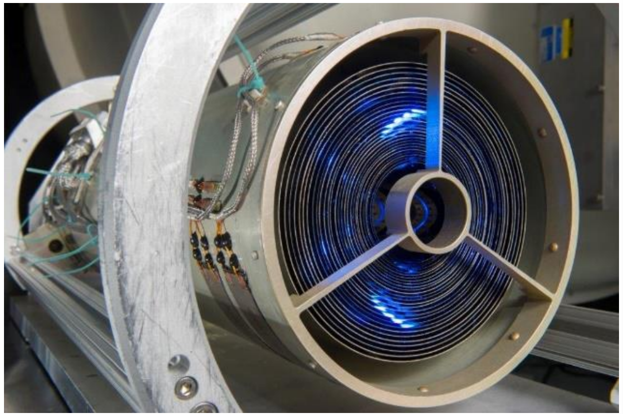
Full-Shell X-Ray Optics

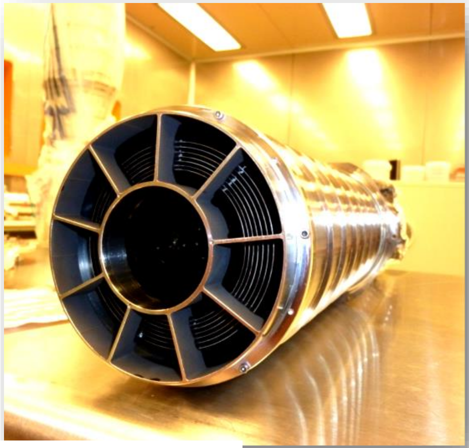
Full-shell optics

60 mm length 50 to 100 mm diameter

Down to 50μm thick

Up to 0.5 m diameter





Shells nested into a module

Down to 0.025 m diameter

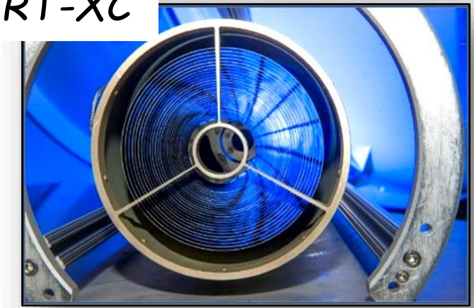
Replicated X-ray Optic Projects at MSFC

Astronomical applications

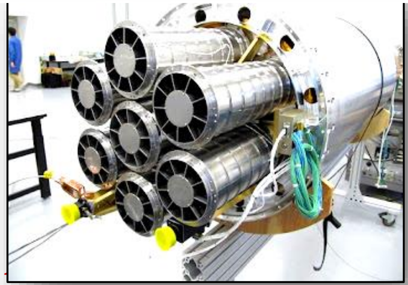
Past

HERO/Super HERO/HEROES

ART-XC

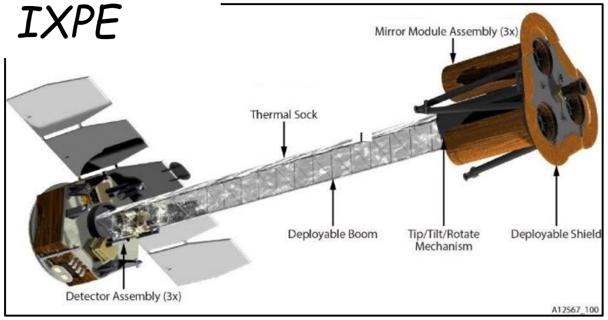


FOXSI/FOXSI-2/FOXSI SMEX

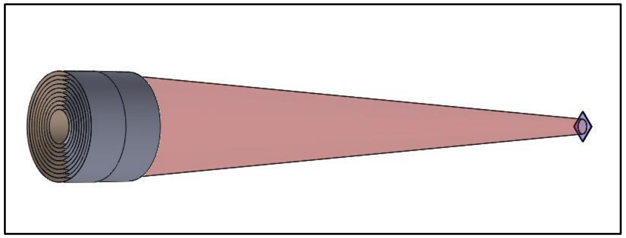


Current

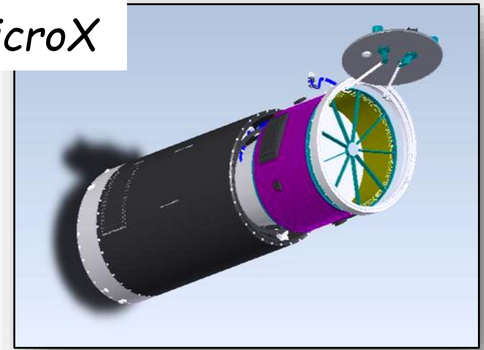
IXPE



MIXO

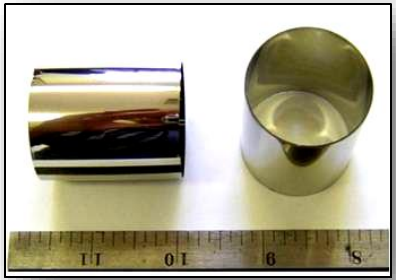


MicroX

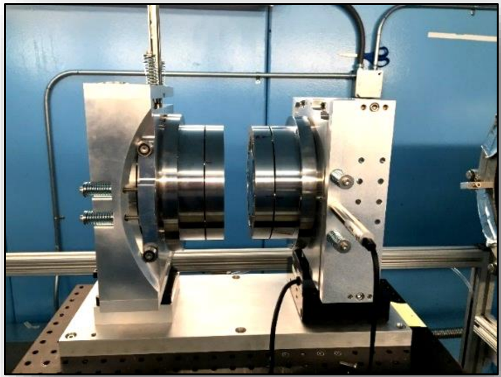


Non-astronomical applications

Medical imaging



Neutron imaging



X-Ray

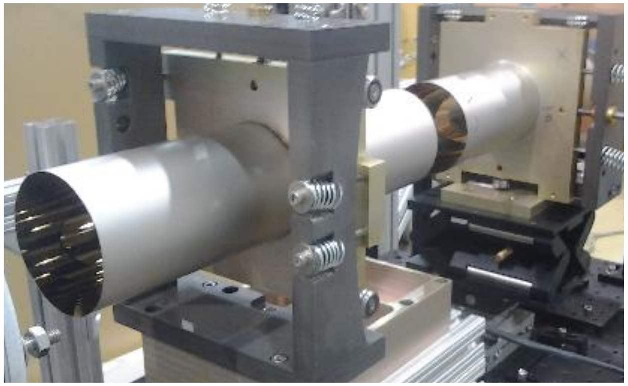
Flight X-ray Optics at MSFC

	IXPE	ART-XC	FOXSI	HERO
Energy range (keV)	2 - 10	5 - 30	5 - 15	20 - 70
Optics Effective area	1000 cm^2 at 3 keV	≥ 455 cm^2 at 8 keV	150 cm^2 at 10 keV	95 cm^2 at 40 keV, 50 cm^2 at 60 keV
Number of Modules	3	7 (plus 1 spare)	7	8
Focal length (m)	4.0	2.7	2.0	6.0
Number of shells per module	24	28	7	14
Shell diameter range (mm)	162 - 272	50 - 150	76 - 103	50 - 94
Coating	-	Ir	Ir	Ir
Shell thickness (microns)	180 - 250	250 - 325	250	250

Spinoff Application: Neutron Microscopy

***<u>Collaboration</u>*: NASA MSFC, NIST, MIT**

- Project aims to build the world's first neutron microscope
- Re-envisioning and shaping the future of neutron imaging
- Cold neutron imaging requires similar graze angles as X-rays
- Potential for many commercial applications



Neutron microscope prototype (2013)
(shells are made from the parabolic segments of existing FOXSI mandrels)

Requirements

- ***10 shell pairs. Parabola-parabola***
- ***<u>1 arc sec FWHM resolution</u>***

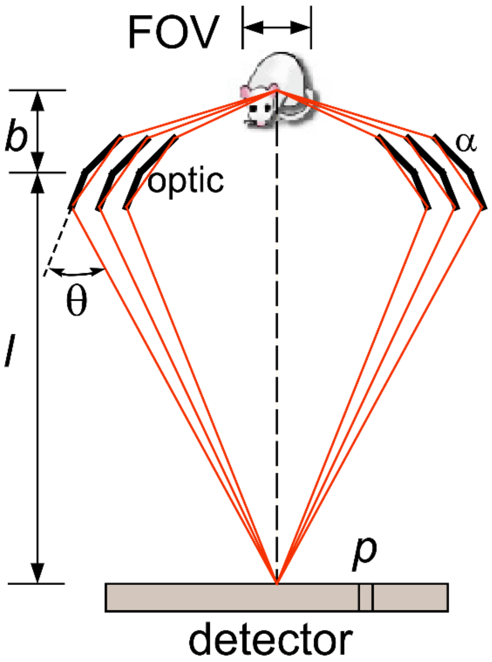
Mikhail V. Gubarev ; et.al; From x-ray telescopes to neutron focusing. Proc. SPIE 8147, Optics for EUV, X-Ray, and Gamma-Ray Astronomy V, 81470B (September 30, 2011); doi:10.1117/12.897325.

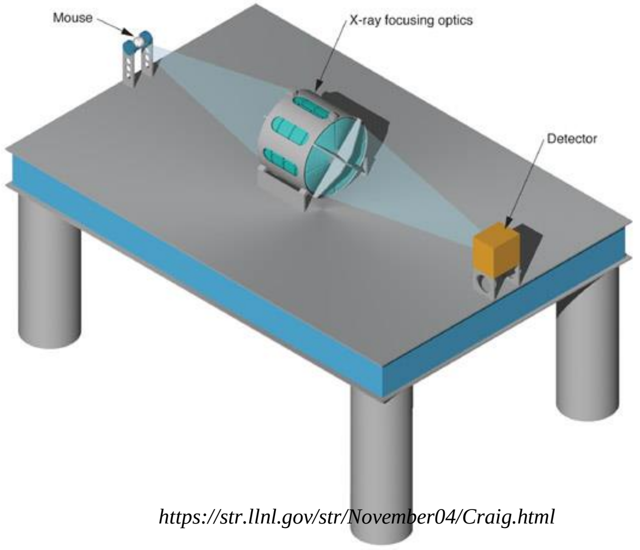
Spinoff Application: Radionuclide imaging

MEDICAL IMAGING

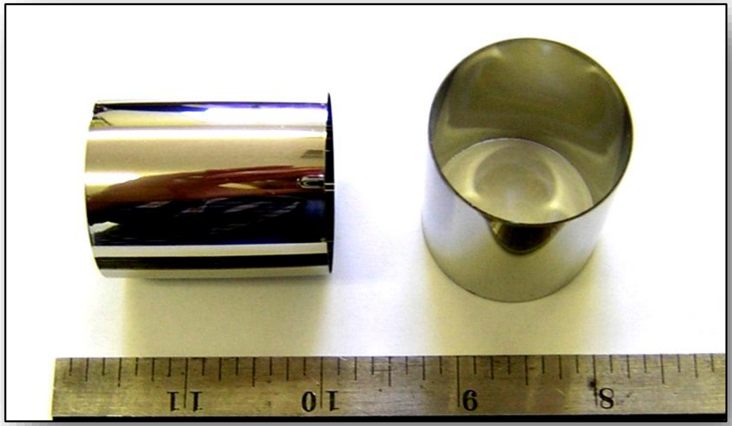
- Animal imaging technology important for biomedical science
  E.g., therapeutic development, disease study

- Non-invasive imaging plays a crucial role in anatomical studies
  Ultrasound: ~200 µm resolution
  CT & MRI: 25–50 µm resolution
  Functional & Metabolic studies
  SPECT & PET: ~1 mm resolution





https://str.llnl.gov/str/November04/Craig.html



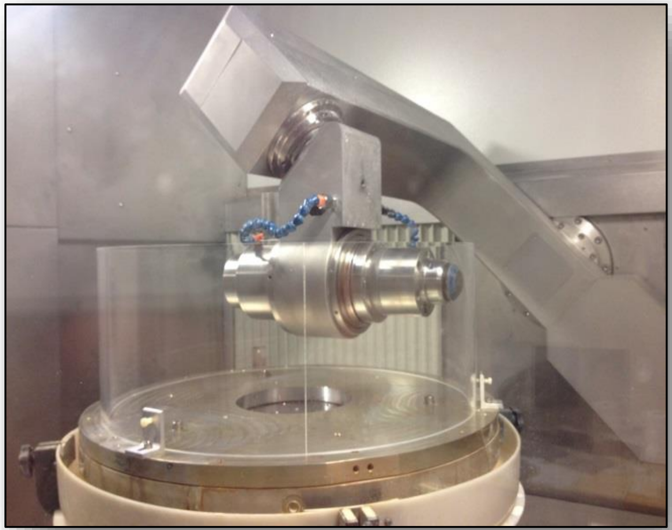
https://e-reports-ext.llnl.gov/pdf/305422.pdf

Ongoing Improvements

- Typical resolutions are ~ 25 arcsec HPD and ~4-10 arcsec FWHM for our production optics
- Efforts underway to improve the resolution include:
    - Better quality mandrels
    - Lower-stress electroforming
    - Direct fabrication (& polishing)
    - Post-fabrication figure correction
    - More precise alignment and assembly
- The near-term goal is a few arcsec HPD and arcsec-level FWHM

Improved Mandrels: Zeeko Polishing Machine

- The machine utilizes a “bonnet” technique in which an inflated rubber hemispherical diaphragm supports the polishing medium.
- There are different “bonnet” sizes (20 mm, 40 mm and 80 mm radii of curvature)
- This computer-controlled deterministic polishing processes leads to a high convergence rate.
- Tool path generation (**TPG**) software had to be developed.
- Direct-fabrication of X-ray mirror



Improved Mandrels: Zeeko Polishing Machine

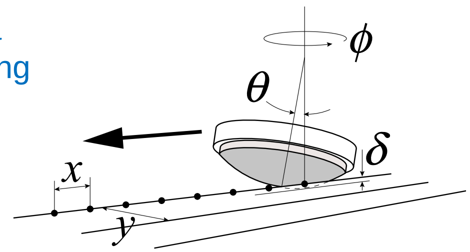
Parametric wear pattern simulation enables a more efficient method of exploring the polishing parameter space.

Wear rate is proportional to :

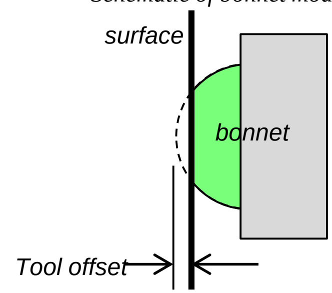
- Velocity of bonnet depends on
  - Spindle rotation
  - Head attack angles
- Bonnet pressure depends on
  - Internal pressure of bonnet
  - Bonnet structural and mechanical properties

Parameter optimization

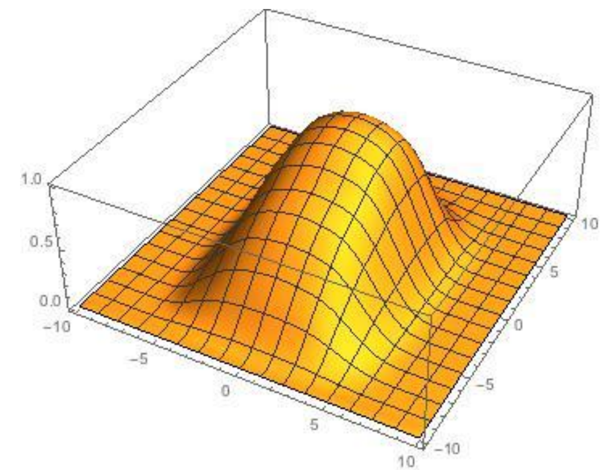
Bonnet pressure
Spindle speed
Tool Offset



Schematic of bonnet model

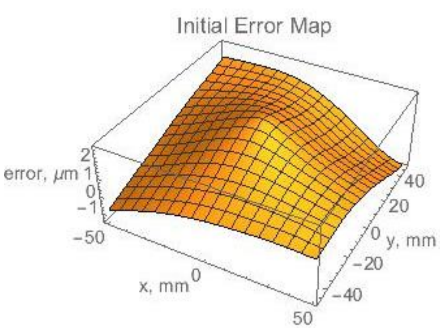


Measured wear function



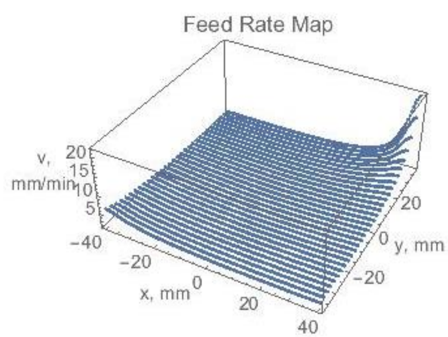
Wear function characterization

Richardson-Lucy deconvolution algorithm + small nonlinear correction (Tends to generate smoother edge transitions)



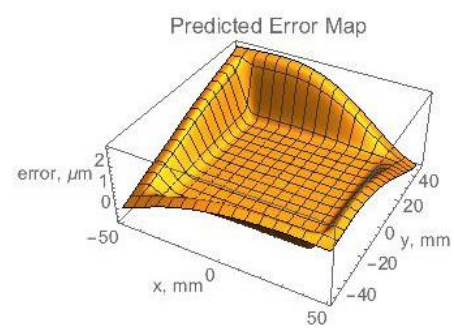
Initial error map derived from metrology data.

RMS slope errors along x-axis are ***8 arcsec.***



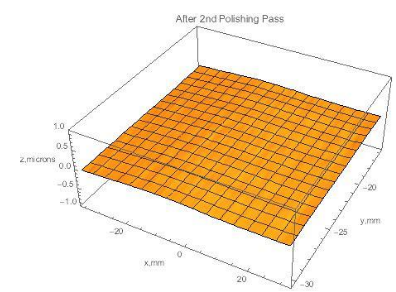
Derived feed rate map.

Feed rates range from 1.35-20 mm/min.



Predicted result of polishing iteration.

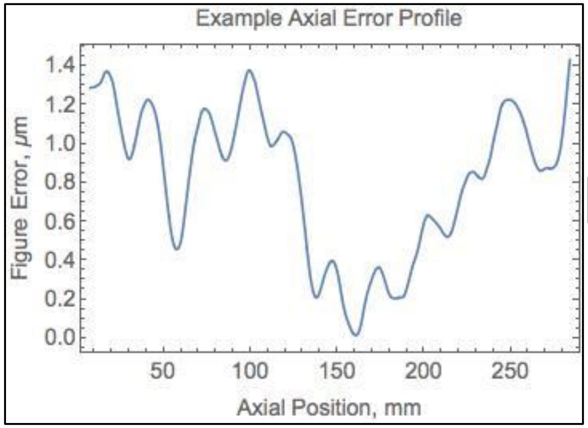
Predicted RMS slope errors are ***0.6 arcsec***

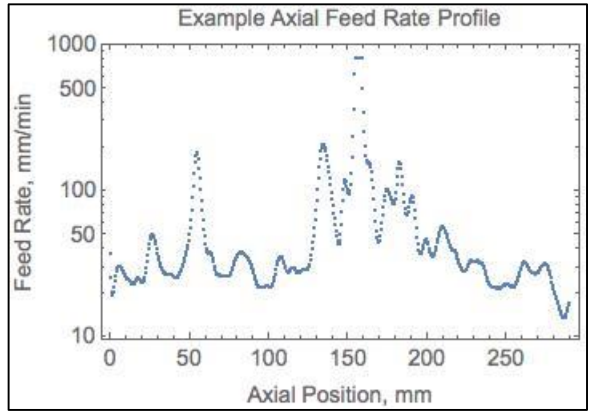


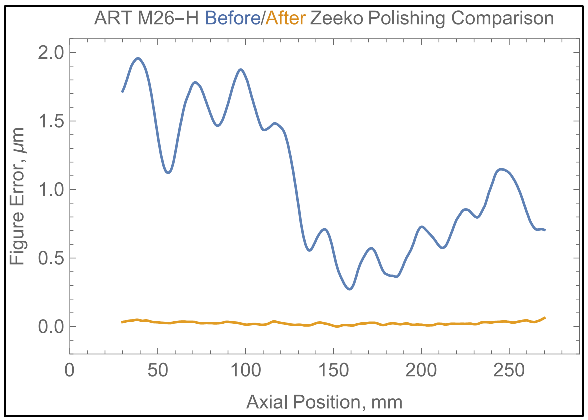
Error map derived from metrology data.

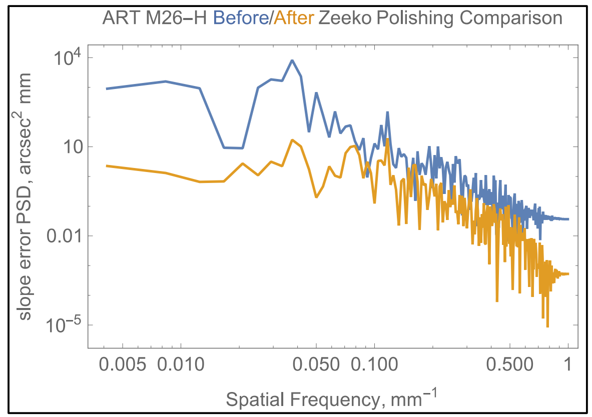
RMS slope errors were reduced to ***0.5 arcsec***

Mandrel Demonstration









Mandrel > 5x better than any made with conventional polishing

	before	after
Figure error (St. Dev.)	**500 nm**	**10.7 nm**
Slope error (> 2 cm) (RMS)	**6.32 arcsec**	**0.30 arcsec**
Low frequency (> 7 cm) slope error (RMS)	**2.66 arcsec**	**0.09 arcsec**
Mid frequency (2-7 cm) slope error (RMS)	**5.73 arcsec**	**0.29 arcsec**

Lower electroforming stresses: Pulsed Plating

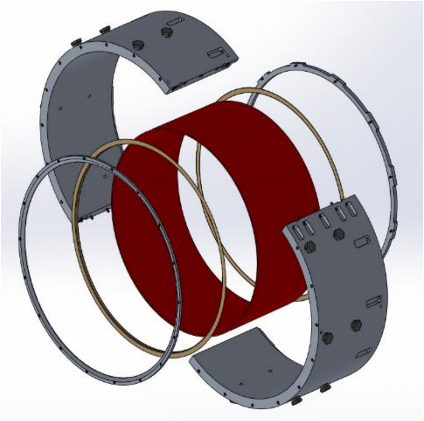
- Reduce stress variations in electroforming through pulsed plating.
    - Periodic reversal of polarity\during electroforming alternates deposition with selective etching, providing a finer grain structure and denser packing.
    - Recent evidence shows that the shells plated this way are very low stress and closer to the mandrel shape than with conventional electroforming.

- Circularity is key for a good FWHM - Pulsed plating of pure nickel recently demonstrated the micron-level circularity necessary for arc-second-level FWHM resolution.

Full-Shell Direct Fabrication

- Technology development - figure and polish thin x-ray metal optics directly
- Finite-Element Analysis - thickness ~ 1.5 mm will be stable enough to be polished directly
- Metal substrates
  - improve the mechanical stability,
  - Single-point diamond turning instead of grinding process
- Computer controlled deterministic polishing

Backing support system - A thin layer of backing material (not shown) acts as an interface between the mirror shell (red) and the stiff outer support clam-shell (gray).



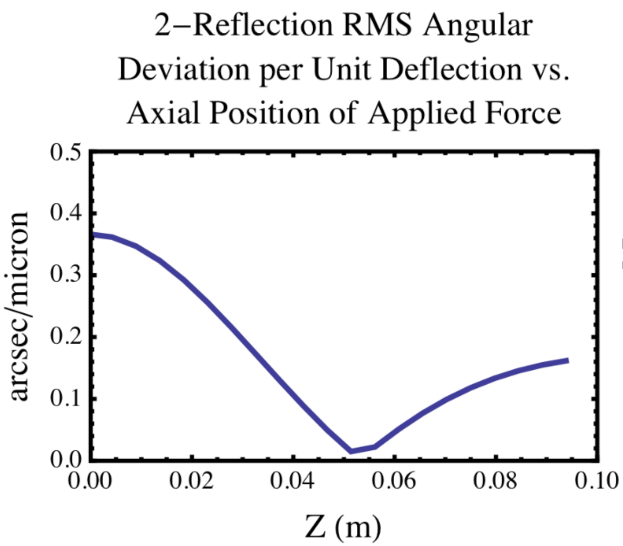
- In situ metrology system - Phase-Measuring Deflectometry (PMD): Deviations from perfect spacing of fringe pattern measured at multiple phases provides an unambiguous measure of slope deviations of the mirror
- Developed fixtures to provide uniform back support to the entire shell during figuring and polishing
  - Stiff outer shell and a thin layer of backing/interface material that goes between the mirror shell and the outer support
    - High-viscosity liquids
    - Pitch
    - Granular materials - spherical glass beads

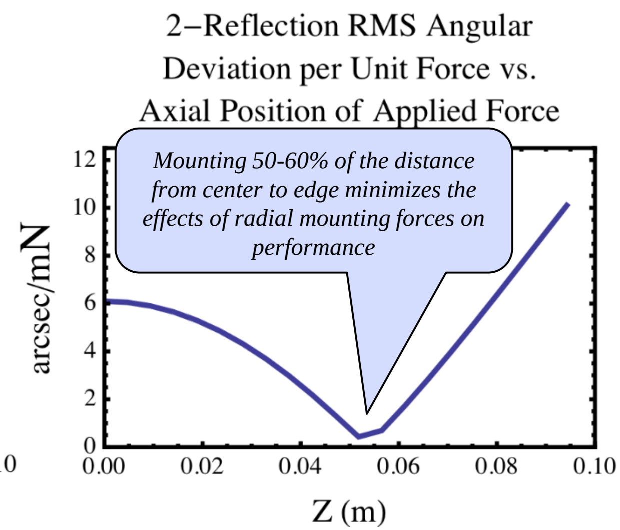
M. Gubarev ; B. Ramsey ; J. K. Kolodziejczak ; W. S. Smith ; J. Roche ; W. Jones ; C. Griffith ; T. Kester ; C. Atkins ; W. Arnold;
Direct fabrication of full-shell x-ray optics . Proc. SPIE 9603, Optics for EUV, X-Ray, and Gamma-Ray Astronomy VII, 96030V (September 4, 2015);
doi:10.1117/12.2190020.

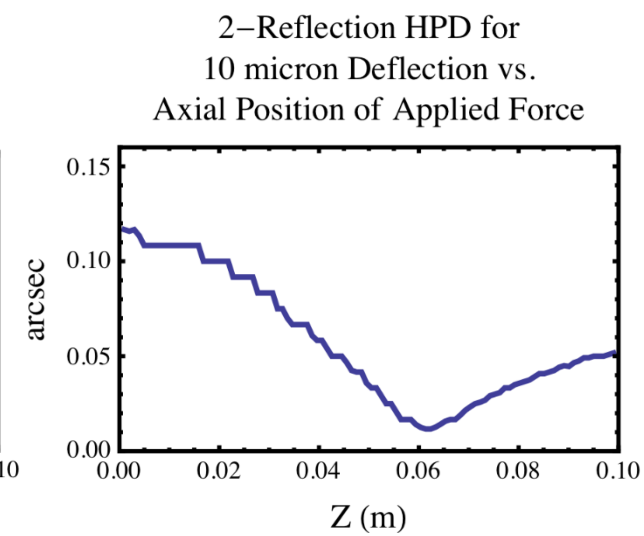
Mounting Optimization

Performance vs. Axial Mounting Location

- The performance analysis of the cylindrical shell was performed, using both analytical methods and finite element analysis (FEA).
- Analytical methods were applied in Mathematica® and detailed finite element models (FEMs) were made in ANSYS.







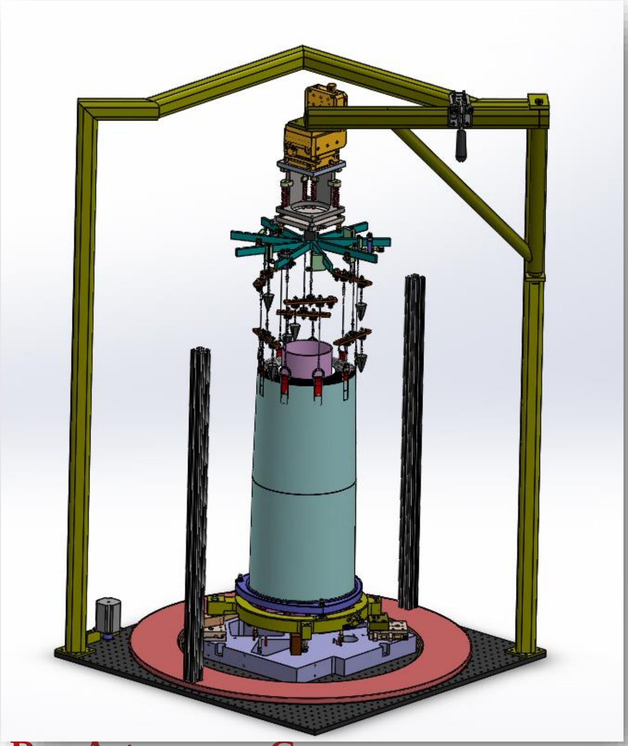
Analytical models

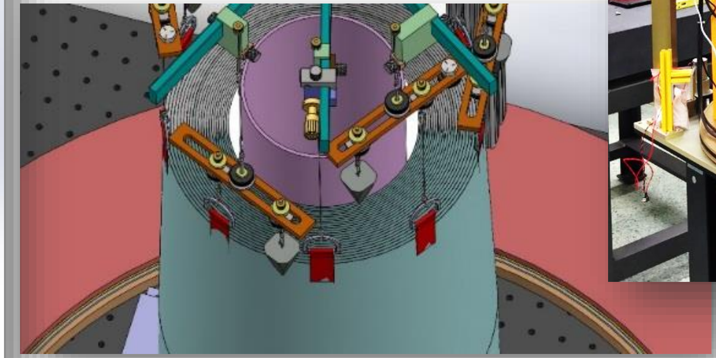
FEA simulations

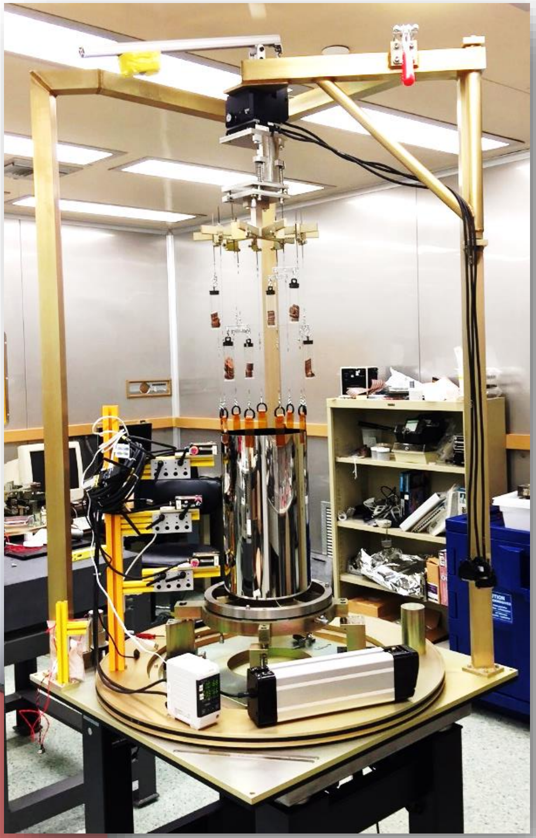
Jacqueline M. Roche et.al, Opto-mechanical analyses for performance optimization of lightweight grazing-incidence mirrors . Proc. SPIE 8861, Optics for EUV, X-Ray, and Gamma-Ray Astronomy VI, 88611G (September 26, 2013); doi:10.1117/12.2026884.

Alignment

- Strings approach – mirror is hung with strings
- Holding at the opposite end to the glue positions
- Equalizing the strings tension – self leveling and minimum distortions
- Off loading weight to the strings





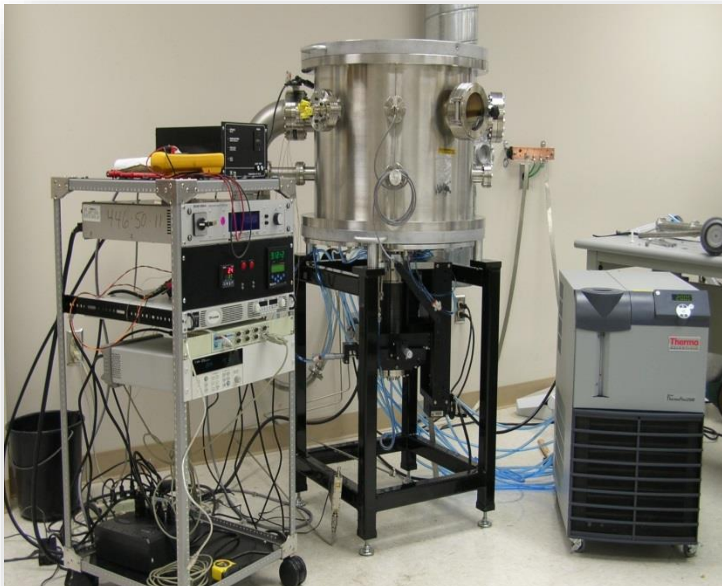


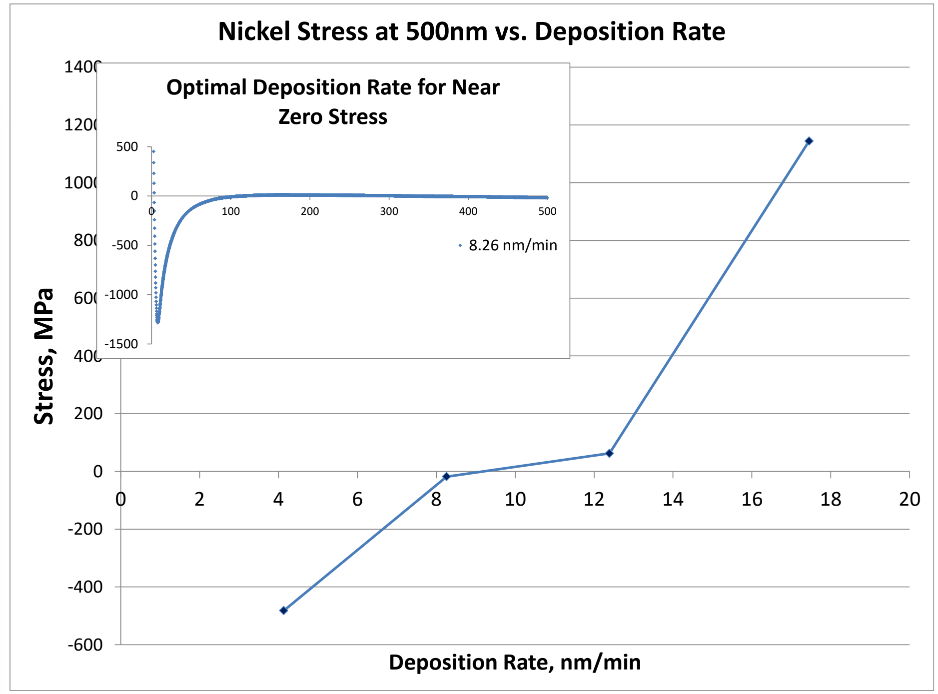
Metal – Ceramic Hybrid Shells

***Collaboration*: NASA MSFC, SAO, ReliaCoat**

- Plasma thermal spray technology
- To replace the high density Nickel with light ceramic compound
- Ni density - 8.9 g/cm^3; Ceramic compound density – ~2.5 g/cm^3
- Reduce the weight of the optic – keep the advantages of electroform nickel replication

In-Situ Stress Measurement





Preliminary measurements showing coating stress versus deposition rate at fixed gas pressure. Inset shows stress versus coating thickness (nm) at fixed deposition rate

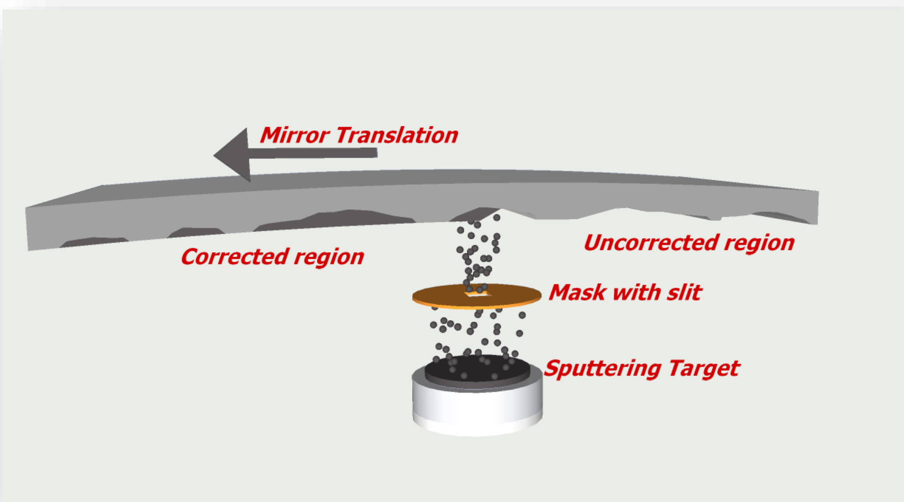
Figure Correction: Differential Deposition

What Differential deposition is a technique for correcting figure errors in optics

How Use physical vapor deposition to selectively deposit material on the mirror surface to smooth out figure imperfections

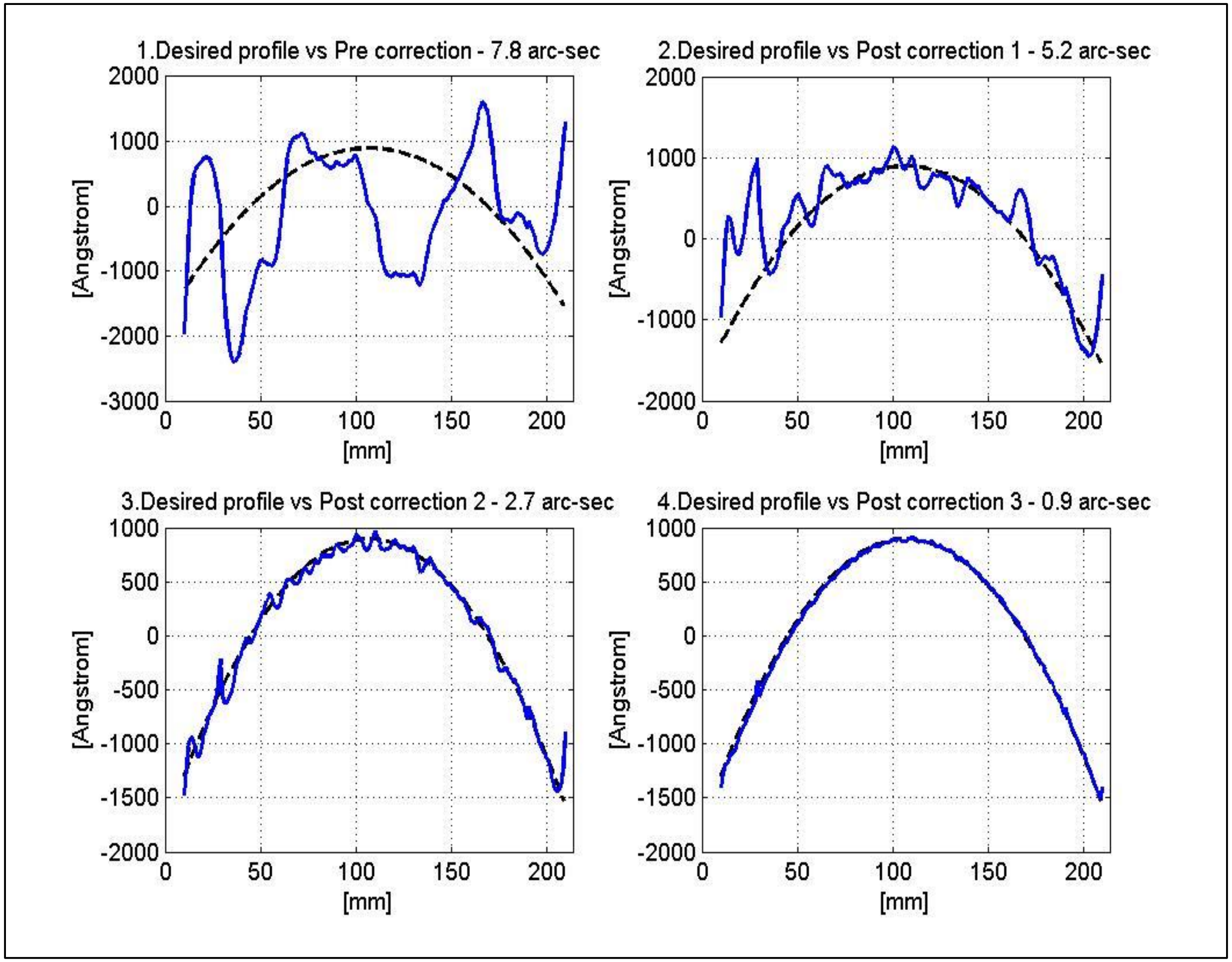
Why

- Can be used on **any type** of optic, full-shell or segmented, mounted or unmounted
- Can be used to correct a wide range of spatial errors. Could be used in conjunction with other techniques… e.g. active optics.



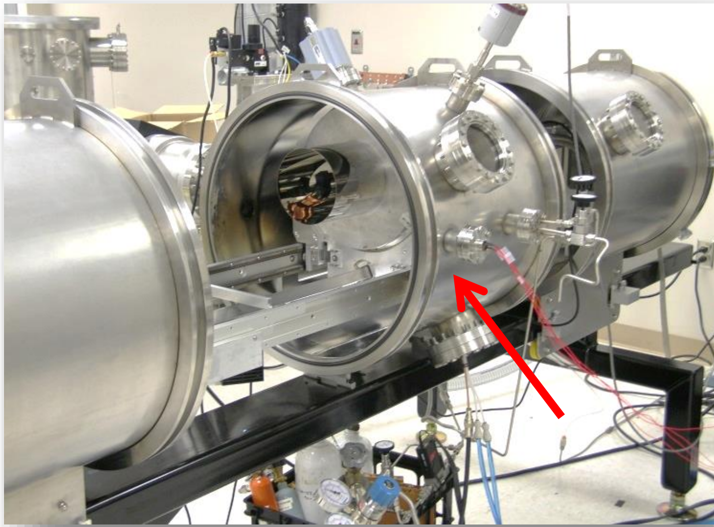
Surface profile metrology
↓
Develop correction profile "Hitmap"
↓
Simulations – translation velocity of shell
↓
Differential deposition
↓
Surface profile metrology
↓
X-ray testing

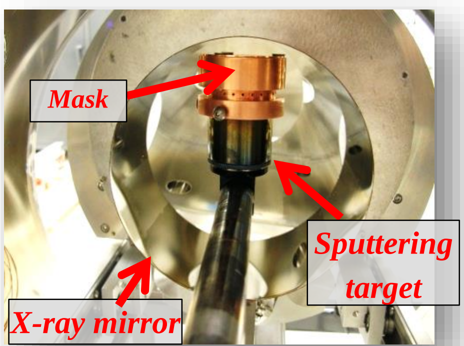
Process Sequence – Differential Deposition



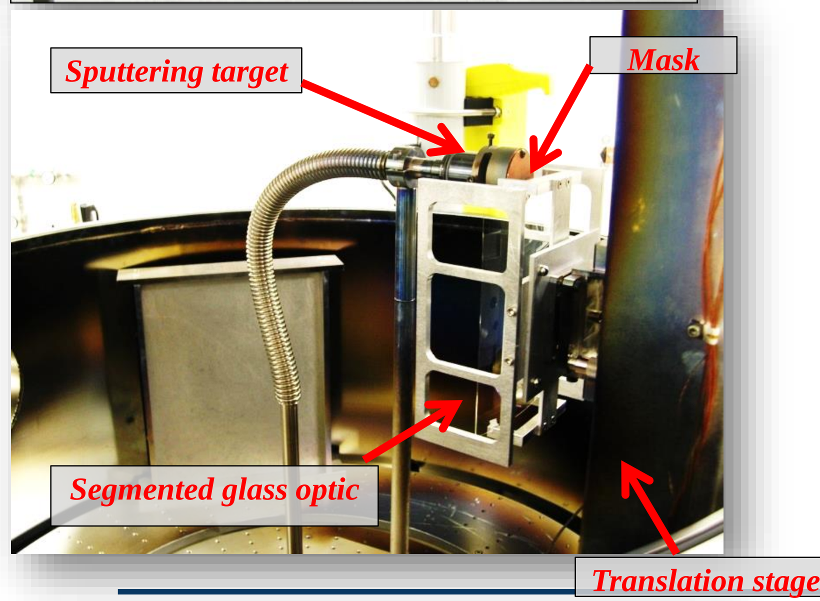
Simulated correction sequence showing parabolic axial figure profile before (top left) and after 3 stages of correction using a beam of FWHM = 14mm, 5.2 mm and 1.7 mm respectively. The dotted line gives the desired figure and the solid line gives the figure obtained at each stage. Overall, resolution improved from 7.8 arcsec to 0.9 arcsec HEW (2 bounce equivalent).

Coating systems



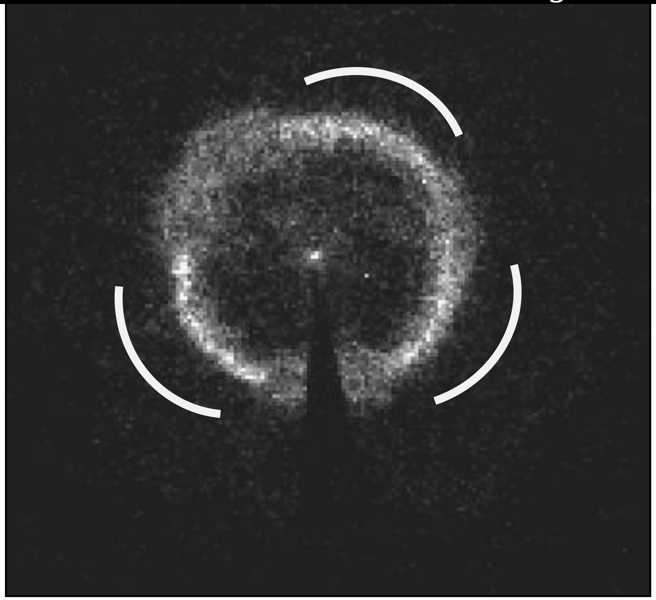


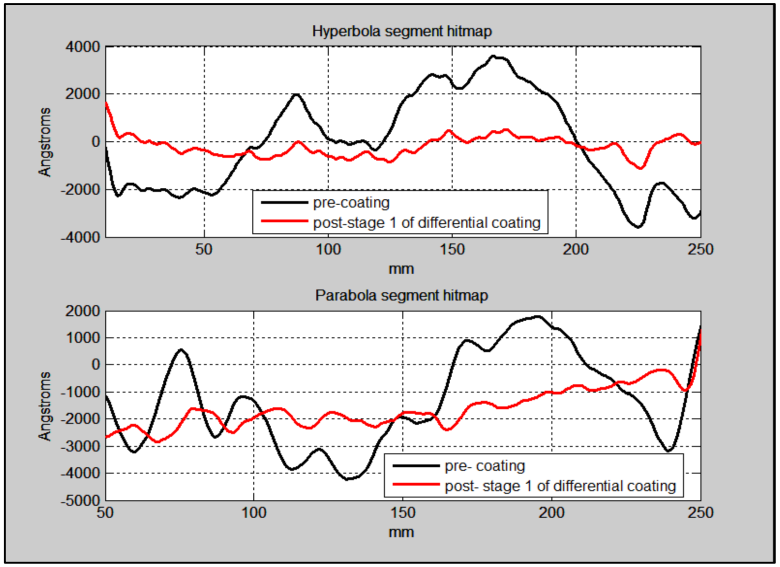
Sputtering head with copper mask positioned inside shell



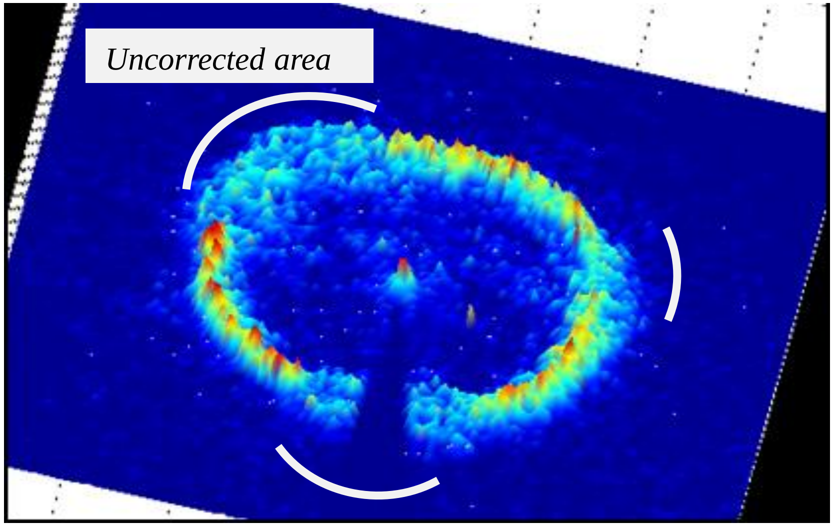
X-ray testing – pre-and post- differential coating

Marked areas - corrected azimuthal segments



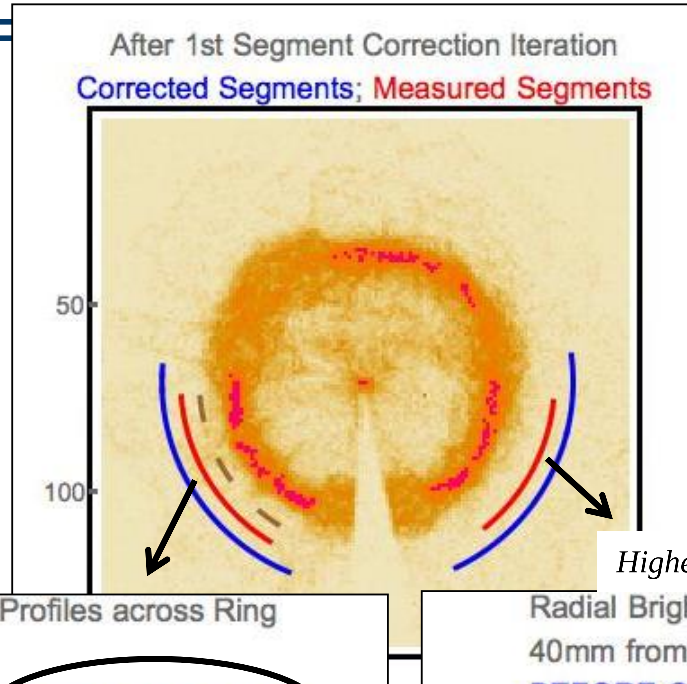


- Plots shows intra-focus X-ray image (-40 mm) of the corrected shell
- Corrected segments are visually obvious compared to the uncorrected in X-ray testing with the CCD

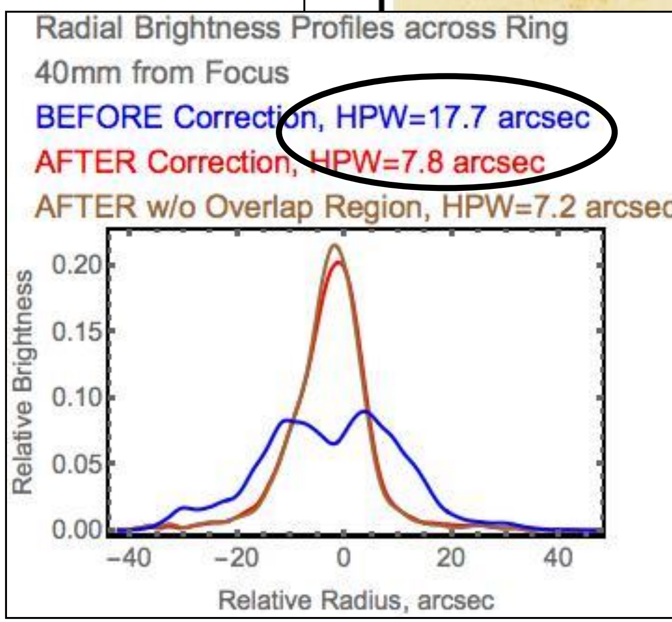


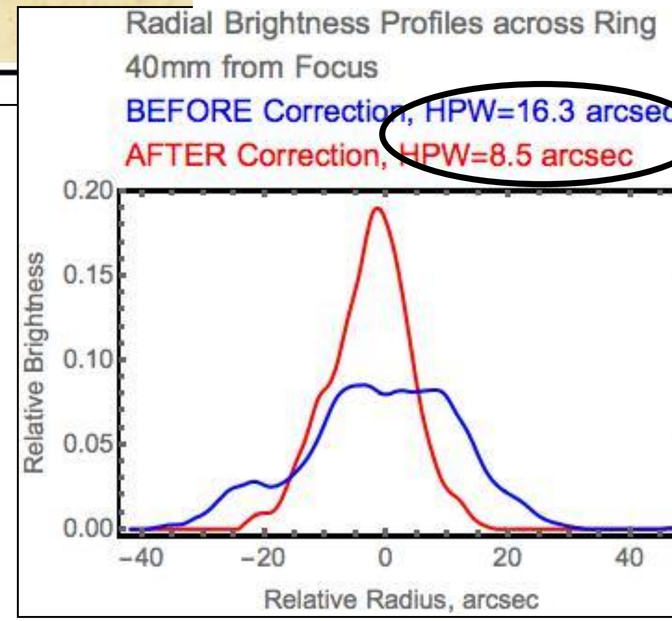
X-ray testing – pre-and post- differential coating

A factor of >2 improvement is achieved with one stage of correction



Higher frequency- correction





Conclusion

- Full-Shell Optics at MSFC
  - Electroform nickel replication has been used for past 20 years for satellite, rocket and balloon-borne missions and for various spin-off applications
- Improvements are underway
  - Better quality mandrels
  - Lower-stress electroforming
  - Direct fabrication (& polishing)
  - Post-fabrication figure correction
  - More precise alignment and assembly